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This project focused on developing algorithms for multi-vehicle, cooperative surveillance and reconnaissance that operate in a modern net-centric environment. These algorithms take into account the packet-based nature of modern networks by coding information in a manner that makes the performance of the system robust to packet less, variable latency, and repeated transmissions. Results include analysis and design of estimation and control algorithms in the presence of packet loss and across multi-hop data networks, distributed estimation and sensor fusion algorithms for networked environments, development of sensor selection and coverage techniques for spatio-temporal planning, and analysis of robustness to process uncertainty and computational node failure. Applications include cooperative estimation, formation management, and semi-autonomous ISR.

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PACKET-BASED CONTROL ALGORITHMS FOR COOPERATIVE SURVEILLANCE AND RECONNAISSANCE

Final Report
AFOSR GRANT FA9550-04-01-0169

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Abstract

This project focused on developing algorithms for multi-vehicle, cooperative surveillance and reconnaissance that operate in a modern net-centric environment. These algorithms take into account the packet-based nature of modern networks by coding information in a manner that makes the performance of the system robust to packet loss, variable latency, and repeated transmissions. Results include analysis and design of estimation and control algorithms in the presence of packet loss and across multi-hop data networks, distributed estimation and sensor fusion algorithms for networked environments, development of sensor selection and coverage techniques for spatio-temporal planning, and analysis of robustness to process uncertainty and computational node failure. Applications include cooperative estimation, formation management, and semi-autonomous ISR.

1 Introduction

Modern control theory is largely based on the abstraction that information ("signals") are transmitted along perfect communication channels and that computation is either instantaneous (continuous time) or periodic (discrete time). Modern communication theory studies imperfect channels but without the strict limits on delays and latency crucial in control. These abstractions have served their fields well for 50 years and have led to many success stories in a wide variety of applications. Future applications of control in network-centric systems will be much more information-rich than those of the past and will involve networked communications, distributed computing, and higher levels of logic and decision-making. New theory, algorithms, and demonstrations must be developed in which the basic input/output signals are data packets that may arrive at variable times, not necessarily in order, and sometimes not at all. Networks between sensors, actuation, and computation must be taken into account, and algorithms must address the tradeoff between accuracy and computation time. Progress will require significantly more interaction between information theory, computer science, and control than ever before.

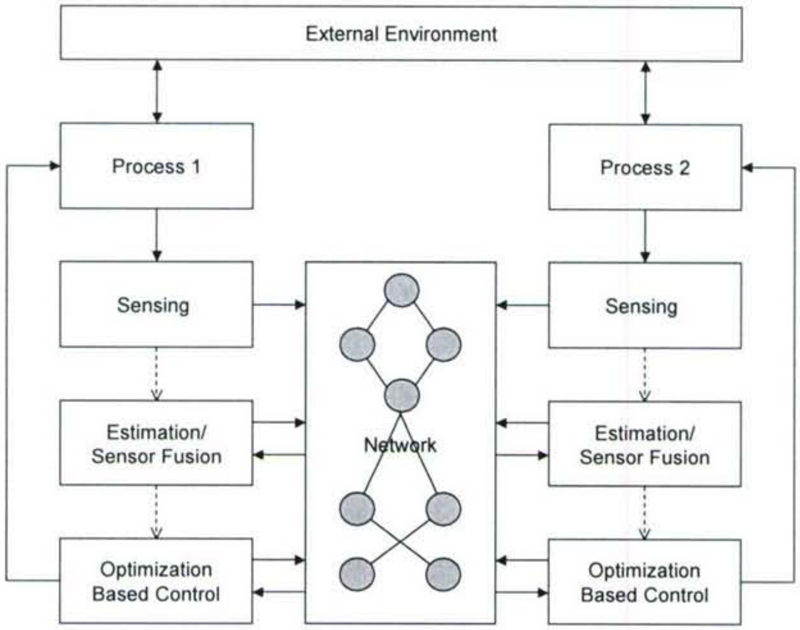

Figure 1: Control architecture for a networked control system.

An emerging architecture for networked control systems is shown in Figure 1. This architecture separates the traditional elements of sensing, estimation, control, and actuation for a given system across a network and also allows sharing of information between systems. Careful decisions need to be made on how the individual components in this architecture are implemented and how the communications across the networked elements is managed. This architecture can be used to model either a single system (using either half of the diagram) or multiple systems that interact through the network.

2 Accomplishments

Over the three years of this project, we developed results in estimation and control across communication channels with limited bandwidth, using simple models for the effects of packet loss.

2.1 Dynamic Sensor Coverage and Sensor Scheduling

We have considered the problem of active sensing using mobile sensor nodes that are jointly estimating the state of a dynamic target as a sensor network [1]. We propose a gradient search-based decentralized algorithm that demonstrates the benefits of distributed sensing. We then examine the task of tracking multiple targets. We use a greedy algorithm for associating sensors with targets along with the gradient search strategy for sensor vehicle motion planning. Simulation results show that these simple

decentralized strategies perform quite well and the sensor nodes exhibit interesting cooperative behavior.

We have also considered a situation in which many sensors co-operate to estimate a process [4]. Only one sensor can take a measurement at any time step. We wish to come up with optimal sensor scheduling algorithms. The problem is motivated by the use of sonar range-finders used by the vehicles on the Caltech Multi-Vehicle Wireless Testbed. This problem involves searching a tree in general and we analyze two strategies for pruning the tree to keep the computation limited. The first is a sliding window strategy motivated by the Viterbi algorithm, and the second one uses thresholding. We also consider a technique that employs choosing the sensors randomly from a probability distribution which can then be optimized. The performance of the algorithms has been illustrated with the help of numerical examples.

For the problem of cooperative surveillance and reconnaissance, the results above most be extended to include decision on what information is sent across the network (sensor scheduling) and where the sensor are places as a function of time (sensor coverage).

In joint work with David Jeffcoat at AFRL/MN [25], we developed a theoretical framework for the dynamic sensor coverage problem for a simple case with multiple discrete time linear dynamical systems located in different spatial locations. The objective is to keep an appreciable estimate of the states of the systems at all times by deploying a few mobile sensors. The sensors are assumed to have a limited range and they implement a Kalman filter to estimate the states of all the systems. The motion of the sensor is modeled as a discrete time discrete state Markov chain. Based on some recent results on the Kalman filtering problem with intermittent observations by Sinopoli et. al., we derive conditions under which a single sensor fails to solve the coverage problem. We also give conditions under which we can guarantee that a single sensor is enough to solve the dynamic coverage problem.

A slightly more general set of results was developed in [5], in which we consider the problem of a set of sensors is jointly trying to estimate a process. One sensor takes a measurement at every time step and the measurements are then exchanged among all the sensors. We seek to find the sensor schedule that results in the minimum error covariance and describe a stochastic sensor selection strategy that is easy to implement and is computationally tractable. In the sensor selection problem, there are multiple sensors that cannot operate simultaneously (eg, sonars in the same frequency band). Thus measurements need to be scheduled. In the sensor coverage problem, a geographical area needs to be covered by mobile sensors each with limited range. Thus from every position, the sensors obtain a different viewpoint of the area and the sensors need to optimize their positions.

2.2 Estimation and Control with Information Loss

Through a sequence of results, we have explored the performance of estimation algorithms in the presence of networked channels in which information can be lost. This work builds on the recent results of Sinopoli *et al.* in which they develop bounds on

the performance of a Kalman filter in the presence of packet loss.

In [18], we consider a discrete time state estimation problem over a packet-based network. In each discrete time step, the measurement is sent to a Kalman filter with some probability that it is received or dropped. The previous work of Sinopoli *et al.* on Kalman filtering with intermittent observation losses shows that there exists a certain threshold of the packet dropping rate below which the estimator is stable in the expected sense. In their analysis, they assume that packets are dropped independently between all time steps. We have developed a different point of view that extends this analysis in two ways. First, we do not required that the packets are dropped independently but just that the information gain π_g—defined to be the limit of the ratio of the number of received packets n during N time steps as N goes to infinity—exists. Second, we show that for any given π_g, as long as $\pi_g > 0$, the estimator is stable almost surely, i.e. for any given $\epsilon > 0$ the error covariance matrix P_k is bounded by a finite matrix M, with probability $1 - \epsilon$. Given an error tolerance M, π_g can in turn be found. We also give explicit formula for the relationship between M and ϵ.

Another approach that we have explored is the use of multi-description source coding [12, 13, 11]. In this work, we split the information that we wish to send across multiple packets, but encode the information so that if any collection of packets are lost, the resulting information has a known level of distortion. We have considered two cases: when the packet loss over network links occurs in an i.i.d. fashion or in a bursty fashion. Compared with the traditional single description source coding, multi-description (MD) coding scheme can greatly improve the performance of Kalman filtering over a large set of packet loss scenarios in both cases.

We have also considered the problem of (optimal) control in the presence of packet loss [10, 7]. We first prove a separation principle that allows us to solve this problem using a standard LQR state-feedback design, along with an optimal algorithm for propagating and using the information across the unreliable link. Then we present one such optimal algorithm, which consists of a Kalman filter at the sensor side of the link, and a switched linear filter at the controller side. Our design does not assume any statistical model of the packet drop events, and is thus optimal for any arbitrary packet drop pattern. Further, the solution is appealing from a practical point of view because it can be implemented as a small modification of an existing LQG control design.

We have extended this work in three ways to consider more realistic networks, where information may route through multiple nodes before being delivered to its destination.

In the first work, we consider the use of multi-hop protocols for improving the convergence rates of consensus algorithms [14]. We propose multi-hop relay protocols based on the current "nearest neighbor rules" consensus protocols. By employing multiple-hop paths in the network, more information is passed around and each agent enlarges its "available" neighborhood. We demonstrate that these relay protocols can increase the algebraic connectivity without physically adding or changing any communication links. Moreover, time delay sensitivity of relay protocols are discussed

in detail. We point out that a trade off exists between convergence performance and time delay robustness. Simulation results are also provided to verify the efficiency of relay protocols.

We have also considered the problem of data transmissions over networks, where each node in the network is allowed to perform some amount of computation [6]. We consider the problem of determining the optimal processing at each node in the network and provide a strategy that yields the optimal performance at the cost of constant memory and processing at each node. We also provide conditions on the network for the estimate error covariance to be stable under this algorithm. This approach is applicable for networks of sensors that are performing spatio-temporal tasks such as cooperative situational awareness.

Finally, we have also explored the design of control strategies over lossy networks [3, 9]. A network is assumed to exist between the sensor and the controller and between the latter and the actuator. Packets are dropped according to a Bernoulli independent process, with γ and μ being the probabilities of losing an observation packet and a control packet respectively, at time any instant t. A receding horizon control scheme is proposed for the Linear Quadratic Control (LQG) problem. At each instant N future control inputs are sent in addition to the current one. Under this scheme the separation of estimation and control is shown and stability conditions, dependent on loss probabilities, are provided. Simulations show how the overall performance, in terms of lower cost, increases with the length of the horizon.

2.3 Distributed Sensor Fusion Using Dynamic Consensus

A complementary way to explore distributed sensor fusion is to make use of previous results developed under AFOSR MURI funding on consensus algorithms. A consensus algorithm seeks to get agreement between a set of distributed agents on a common quantity. In [23] we examined several dynamical aspects of average consensus in mobile networks. The results allow consensus on general time-varying signals, and allow tracking analysis using standard frequency-domain techniques. Further, the frequency-domain analysis naturally inspires a robust small-gain version of the algorithm, which tolerates arbitrary non-uniform time delays. Finally, we show how to exploit a dynamical conservation property in order to ensure consensus tracking despite splitting and merging of the underlying mobile network.

This work can be extended to to obtain least-squares fused estimates based on spatially distributed measurements [20]. This mechanism is very robust to changes in the underlying network topology and performance, making it an interesting candidate for sensor fusion on autonomous mobile networks. Examples have been explored to demonstrate the the dependence of the performance on the structure of the underlying network. A more systematic analysis of the performance as various network quantities such as connection density, topology, and bandwidth are varied has also been carried out [22]. Our main contribution is a frequency-domain characterization of the distributed estimator's steady-state performance; this is quantified in terms of a special matrix associated with the connection topology called the graph Laplacian,

and also the rate of message exchange between immediate neighbors in the communication network.

These results have led to a more general formulation of the problem of distributed computing [19]. The main theoretical contribution of this work is a geometric formalism in which to cast distributed systems. This has numerous advantages and naturally parametrizes a wide class of distributed interaction mechanisms in a uniform way. We make use of this framework to present a model for distributed optimization, and we introduce the distributed gradient as a general design tool for synthesizing dynamics for distributed systems. The distributed optimization model is a useful abstraction in its own right and motivates a definition for a distributed extremum. As one might expect, the distributed gradient is zero at a distributed extremum, and the dynamics of a distributed gradient flow must converge to a distributed extremum. This forms the basis for a wide variety of designs, and we are in fact able to recover a widely studied distributed consensus algorithm as a special case.

2.4 Robustness to Process Uncertainty and Node Failure

In most of the work on sensor coverage and distributed sensor fusion, it is assumed that the participating vehicles stay within communications range of each other and maintain overall connectivity of the network. We have analyzed the feasibility aspects of motion planning for groups of agents connected by a range-constrained wireless network [21]. Specifically, we address the difficulties encountered when trajectories are required to preserve the connectedness of the network. The analysis utilizes a quantity called the connectivity robustness of the network, which can be calculated in a distributed fashion, and thus is applicable to distributed motion planning problems arising in control of vehicle networks. Further, these results show that network constraints posed as connectivity robustness constraints have minimal impact on reachability, provided that an appropriate topology control algorithm is implemented. This contrasts with more naive approaches to connectivity maintenance, which can significantly reduce the reachable set.

In [17, 16], we consider a robust network control problem. We consider linear unstable and uncertain discrete time plants with a network between the sensor and controller and the controller and plant. We investigate two defining characteristics of network controlled systems and the impact of uncertainty on the process dynamics (modeled as parametric uncertainty). We compute the minimum data rate and minimum packet arrival rate to ensure stability of the closed loop system.

Another notion of robustness is robustness to failure of individual computational nodes [8]. This type of uncertainty has been considered in the area of distributed computation, but has not been considered in many of the networked estimation and control architectures that have been proposed. For a distributed algorithm to be practical, one should be able to guarantee that the task is still satisfactorily executed even when agents fail to communicate with others or to perform their designated actions correctly. We present a concept of robustness which is well-suited for general distributed algorithms for teams of dynamic agents. Our definition extends a similar

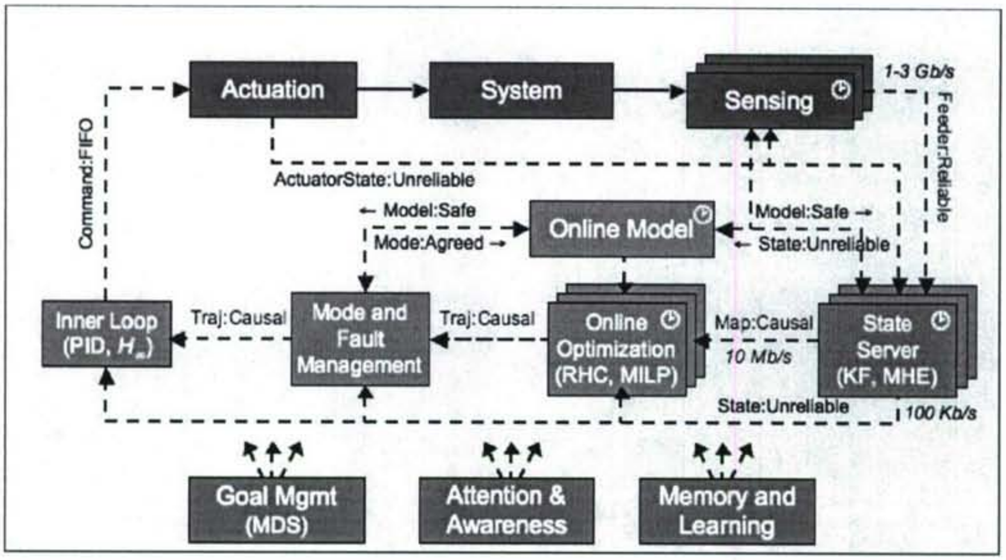

Figure 2: Networked Control Systems Architecture.

notion introduced in the distributed computation literature for consensus problems. We illustrate the definition by considering a variety of algorithms and identify possible ways to make an algorithm robust.

2.5 Networked Control Systems Architecture

In addition to the specific research accomplishments listed above, work on this grant has led to the development of a networked control systems architecture, illustrated in Figure 2, that is serving as the basis for multiple ongoing projects at Caltech. Building on the open source *Spread* group communications protocol, we have developed a modular software architecture that provides inter-computer communications between sets of linked processes. This approach allows the use of significant amounts of distributed computing for sensor processing and optimization-based planning, as well as providing a very flexible backbone for building autonomous systems and fault tolerant computing systems.

This architecture has been interested in and tested as part of Caltech's participation in the 2005 DARPA Grand Challenge [2].

3 Transitions

The overall network architecture developed under this grant was used as part of Caltech's entry in the 2005 DARPA Grand Challenge and will be used in the 2007 DARPA Urban Challenge. Although no direct effort of this grant was applied to the 2005 grand challenge (due to DARPA funding restrictions), the overall framework described above was used as the basis for our networked control systems architecture and has motivated new research directions of high relevance to autonomous vehicles

for Air Force missions. Contact info: Richard Murray (team leader), Caltech, `murray@cds.caltech.edu`.

4 Personnel Supported

Richard M. Murray	Professor, California Institute of Technology
Lars Cremean	Graduate student, Caltech
	Current position: Research Engineer, Aerovironment
Domitilla Del Vecchio	Graduate student, Caltech
	Current position: Assistant Professor, U. Michigan
Nicolas Foirien	Visiting student, Ecole Polytechnique (France)
Melvin Flores	Graduate student, Caltech
Charles Goffin	Visiting student, Ecole Polytechnique (France)
Vijay Gupta	Graduate student, Caltech
	Current position: Postdoc, U. Maryland
Zhipu Jin	Graduate student, Caltech
	Current position: Research Engineer, Cisco Systems
Jeremy Malaize	Visiting student, Ecole des Mines (France)
Ling Shi	Graduate student, Caltech
Abhishek Tiwari	Graduate student, Caltech
	Current position: Research Engineer, Utopia Compression
Demetri Spanos	Graduate student, Caltech
	Current position: Research Engineer, Ab Inventio

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